

**EXPERIMENTS ON ION-CYCLOTRON-WAVE GENERATION USING
AN ELECTROSTATICALLY-SHIELDED RF COIL**

by C. C. Swett, R. Krawec, G. M. Prok, and H. J. Hettel
Lewis Research Center
Cleveland, Ohio

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ABSTRACT

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Power absorption by a hydrogen plasma was investigated using an electrostatically shielded Stix-type rf coil in a continuously operating apparatus. The additional capacitance added to the system by the shield caused the rf vacuum magnetic field of the coil to be spatially nonsinusoidal in the axial direction. A Fourier analysis of the observed field distribution indicates that the coil system generates waves of 44.5- and 89.0-cm wavelengths instead of the single 40-cm wavelength it was designed to produce. Two peaks were observed in power absorption near the ion-cyclotron field. These peaks are attributed to the two waves generated by the coil system rather than one wave plus a particle resonance, which was the previous interpretation. It is suggested that similar distortions of the sinusoidal field may be produced even in unshielded experiments because of the capacitance between the coils and the generated plasma.

Author

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INTRODUCTION

The present investigation was undertaken to study ion-cyclotron-wave generation when a grounded electrostatic shield is used between the Stix-type rf coil and the plasma. The use of a shield in this manner will permit only the induction field to exist under the coil, the electrostatic field of the coil being eliminated from the plasma. Such a con-

figuration is expected to result in the elimination of a number of anomalies that have been observed in plasma experiments when unshielded coils were used. For example, discrepancies between calculated and experimental results have been noted in wavelengths, in the amplitudes of wave components, in the existence of resonances, and in shifts in resonant frequency toward low magnetic field rather than toward high magnetic field with increasing plasma density (refs. 1 to 7). Some of these discrepancies can be attributed to the electrostatic coupling between the coil and the plasma (ref. 2).

Although research has been conducted using a grounded electrostatic shield (ref. 1), some undesirable features existed in the apparatus. The first was that, because of rf-voltage-breakdown problems, the shield was located inside the vacuum chamber and in direct contact with the plasma instead of external to the plasma. This installation necessitated the use of a long conductor (approx. 20 in.) to ground the shield. At a frequency of 6.5 mc, the inductive reactance of this conductor can produce rf voltages on the shield. These voltages, although small, can produce electric fields which are not negligible compared to the azimuthal electric field generated by the induction field. Measurements of the magnitude of the two fields were not made, however. Another undesirable feature was the use of an all-glass system, which was subject to damage due to thermal, electrical, and mechanical stresses.

For these reasons the apparatus has been completely rebuilt. The system now in use is mostly metal with an external shield. Special care was taken to properly ground the shield and to solve the electrical-

breakdown problems. The new apparatus is described herein, and the results obtained with it are compared with those of previous studies.

EXPERIMENTAL EQUIPMENT

A longitudinal cross section of the rebuilt apparatus is shown in figure 1. Hydrogen gas was introduced at the left end of the system and pumped out at the right by means of a 6-inch liquid-nitrogen-trapped diffusion pump. The base pressure of the system was about 10^{-7} torr. The operating pressure (2.0 microns) was controlled by adjustment of the input gas flow and was measured by a McLeod gage having a liquid-nitrogen cold trap. The pressure drop from the gas inlet to the point of pressure measurement was 2 microns.

The plasma source was a hot-cathode discharge as described in reference 8. The filament consisted of six 3-inch-long, 10-mil-diameter tungsten wires. The filament was operated at a negative potential with respect to the main part of the metal vacuum chamber wall that was the anode of the discharge. The apparatus was constructed of stainless steel, except for the 4-inch-I.D. pyrex glass cross at the plasma-source end of the system and the 33-inch aluminum oxide tube (figs. 1 and 2) at the center.

Twelve water-cooled dc coils connected in series and supplied with up to 4400 amperes from remotely controlled generators produced a continuously operating magnetic field variable to 10,000 gauss in the region of the rf coil and 20,000 gauss in the mirrors. The field variation was $\pm 1\frac{1}{4}$ percent in the uniform region and about one half this amount between the centers of the rf coils. The field was calibrated by means of a nuclear-magnetic-resonance gaussmeter.

Details of the rf coil and electrostatic-shield assembly are shown in figure 2. The rf coil was a four-section Stix-type coil (ref. 5) having four turns per section, fabricated with $\frac{3}{8}$ -inch silver-plated copper tubing. The I.D. of the coil was $5\frac{3}{8}$ inches and the wavelength (distance between center of the first coil and center of the third coil) was 40 cm. The inductance of the coil was 1.94×10^{-6} henry and the ac resistance (at 6.5 mc) was 0.273 ohm. The Q of the coil without plasma was 290. The coil was water cooled and the $\frac{1}{2}$ -inch silver-plated copper tube to the matching network was oil cooled.

The electrostatic shield located on the exterior surface of the aluminum-oxide tube was rolled from $\frac{1}{32}$ -inch copper sheet leaving about a 0.7-inch longitudinal slot the full length of the shield. The shield was grounded by a rod to an external cylindrical enclosure that could be pressurized to 15- to 30-psi gage with sulfur hexafluoride gas to prevent rf voltage breakdown. The important current-carrying surfaces of the stainless steel were silver plated.

The electric circuit for the network used to match the impedance of the coil with the impedance of the transmitter has been described in reference 1 and is shown in figure 3. The major changes made to the network were in improvement of the shielding to reduce electromagnetic radiation, in pressurization of the box and components, and in oil cooling of all electrical connections. The coil current was measured by a rf-current transformer placed as shown; the coil voltage was measured by a commercial vacuum-tube voltmeter. A capacitance voltage divider placed across the coil gave a reference signal for magnetic probe measurements. A directional coupler located at the input to the

matching network measured both the power output of the transmitter and any reflected power due to mismatch. The network could be quickly tuned to maintain the reflected power at less than 10 watts under all operating conditions.

Only one measurement (in addition to power absorption) was made for this investigation: the amplitude of the axial magnetic field of the propagated wave. One of the problems in making such measurements in a continuously operating energetic plasma is durability of the probes. A magnetic-probe system that has partially solved the durability problem is shown in figure 4. It is intended for use with probes that measure axial magnetic fields. The shell consisted of a $\frac{1}{2}$ -inch stainless-steel tube 50 inches long that had a longitudinal slot the full length of the tube so that the field could penetrate to the probe coil. The tube was water cooled. A glass tube installed inside the stainless-steel tube provided the vacuum seal. The magnetic-probe coil was inserted into the glass tube and could be moved axially to any desired position. For the present program the position was fixed. The coil used was 20 turns of number 32 AWG wire wound with an I.D. of 0.050 inch. An eight-foot long probe of similar construction was used to probe the vacuum rf field of the coil.

RESULTS AND DISCUSSION

When two coils are connected in series it is expected that the current should be the same through each of the coils, resulting in equal magnetic fields underneath the coils. At high frequencies where mutual coupling must be considered, a calculation of the magnetic field of a center-fed Stix coil, such as that used herein, shows a slightly

nonsinusoidal distribution of the magnetic field even when various distributed capacitances are ignored. The outermost coils have fields slightly greater (approximately 8 percent) than the innermost coils. Any conductors, such as an electrostatic shield or plasma inside the coil, and an enclosure surrounding the coil add capacitances to the system, which contribute further to the unequal distribution of current between the coils and to the resulting unbalance in the magnetic fields.

The reason for this nonuniform current distribution can be demonstrated by using the model shown in figure 5(a). A voltage E is impressed on two coils L_1 and L_2 connected in series. A ground plane is placed so that there are capacitances between each turn of the coil and this plane. If the distributed capacitances are lumped into capacitances C_1 and C_2 the equivalent circuit shown in figure 5(b) is obtained. It is obvious that C_1 has no effect on the relative current distribution; C_2 , however, causes a larger current in L_2 . Hence, a nonuniform magnetic field distribution may be expected if the shield, the plasma, or enclosure adds significant capacitance to the system.

Figure 6 compares values of rf vacuum magnetic fields measured in the present apparatus with values calculated with the assumption that no capacitances are present. The nonsinusoidal distribution of the experimentally measured field is marked, the peak fields under the two outside coils being almost three times larger than under the two inside coils. All the data presented herein were obtained with this nonsinusoidal distribution.

Ion-cyclotron-wave generation was studied in the usual manner by observing power absorption as a function of magnetic field after preconditioning the apparatus. Preconditioning was a very necessary part of the program and involved repeated runs at the magnetic field where maximum power transfer would occur.

The preconditioning procedure was as follows: After being open to the atmosphere the apparatus was evacuated to near base pressure, hydrogen was introduced, and then runs of about 1 minute duration were made with the axial magnetic field adjusted to values near the atomic-hydrogen cyclotron field. This procedure initially resulted in the bottom curve of figure 7, which shows relatively weak power absorption. After a few more runs the middle curve was obtained, and further runs resulted in the top, or fully conditioned, curve. Preconditioning occurred at a much faster rate when the magnetic field was maintained at, or close to, the value for peak power transfer rather than at some other field. It was found that about 12 runs condition the apparatus after the system has been open to the atmosphere for a short time; more runs are required on long exposure to the atmosphere. The two peaks in the power absorption curves (fig. 7) were seen only after the system had been preconditioned.

A typical set of data obtained with a plasma-source discharge current of 20 amperes after the system was preconditioned is shown in figure 8. The range of the magnetic field encompasses both the atomic and molecular resonances. There are regions on the high-field side of the atomic and molecular fields where power absorption is greater, in accordance with the theory for generation of ion-cyclotron-

waves. Near the atomic resonance field, two peaks appear, (fig. 7). Since this region is of prime interest, it was redrawn on an expanded scale (fig. 9(a)) so that it can be directly compared with the amplitude of the magnetic-probe signal (fig. 9(b)). The probe was positioned at a distance of 51 cm from the center of the system (15 cm from the end of the outermost coil). At this distance the vacuum rf magnetic field pick-up signal was negligible. The average electron density was estimated from microwave-interferometer data to be approximately $5 \times 10^{11} \text{ cm}^{-3}$.

It can be seen (fig. 9) that the two prominent peaks in power absorption also appear in the magnetic-probe signals. Such a two-peak structure was observed previously in references 5 and 9, wherein the first peak was attributed to single-particle ion-cyclotron resonance and the second peak to ion-cyclotron-wave generation. We propose herein an alternative explanation: more than one wave is being excited because of the nonsinusoidal nature of the rf field.

A Fourier analysis of the vacuum field (fig. 6) shows that the relative amplitude $B_{r,f}$ of the field along the axis can be represented by the equation:

$$B_{r,f} = 1.31 \sin \frac{2\pi Z}{89} + 1.64 \sin \frac{2\pi Z}{44.5} - 0.36 \sin \frac{2\pi Z}{29.6} + \dots$$

where $Z = 0$ is at one end of the coil system where the field is 0. The first two components are the strong ones and have roughly the same amplitude. Hence, if two waves are present in the plasma, the wavelengths expected would be 44.5 and 89 cm, respectively. The peaks observed in the power absorption would have to correlate in some manner with these values.

The above considerations may also apply to the experiments mentioned previously (refs. 5 and 9) in which unshielded coils were used. No proof can be presented that such considerations are applicable because of the many differences in equipment and operating conditions. However, there is some capacitance between the coils and the plasma, so that the conditions necessary to produce nonsinusoidal fields were present. Vacuum magnetic field measurements would not have shown such distribution, and field measurements with plasma present were not reported.

There are four reasons for believing that the peak nearest the ion-cyclotron field is not a particle resonance. First, the power absorption represented by the first peak is approximately 50 percent of the input power. This amount seems unreasonably high for particle resonance in accordance with theory (ref. 10).

Second, the energy of each particle would have to be very large, if the absorbed power were going into the particles. An estimate based on the number of atomic ions leaving the system per second in a plasma having a density of 10^{12} atomic ions per cubic centimeter indicates that each ion would have to remove about 180 keV of energy.

Third, only one peak should appear in the probe signal amplitude (fig. 9(b)), because a particle resonance should not produce a magnetic-probe signal far from the coil. On the other hand, if the magnetic-probe signal is caused principally by ion-cyclotron-waves, there should be negligible response below the ion-cyclotron field, as was indeed observed (fig. 9(b)). Just above the cyclotron field, the signal increases rapidly to a peak at a field value that corresponds with the power-absorption peak. This behavior also is expected for an ion-cyclotron wave.

Finally, great care was taken in measuring the ion-cyclotron field, in determining the relative position of the peaks, and in trying to observe the particle resonance by itself. No evidence was found that conflicts with the two-wavelength explanation.

If this explanation is correct and the peak nearest the atomic field corresponds to a wavelength of 44.5 cm, the dispersion relation (eq. (26), ref. 10) can be used along with the measured position of this peak to predict the position of the 89-cm component. This method predicts that the 89-cm wave should occur at $\Omega = 0.885$ (Ω is the ratio of wave frequency to ion-cyclotron frequency). The measured value of Ω is 0.890, which agrees with the prediction.

The shorter wavelength components are not likely to appear strong and would probably be masked by the two major wavelengths, especially since the Fourier amplitudes are small. Also they would occur very close to the atomic-ion-cyclotron point where the effects of ion-cyclotron damping are strong.

To confirm more definitely the explanation proposed for the two peaks, the experiment should be rerun with a sinusoidal field distribution. The peak farthest from the cyclotron field should then disappear. There are at least three possible modifications that can be made to obtain such a field distribution. One way is to reduce the number of turns on the outermost coils. Another is to add capacitance across the innermost coils to increase the current through them. The third way is to add short-circuiting loops near the outermost coils to reduce the inductance of these coils. The final configuration might require a combination of these, and perhaps even finer adjustments

of the field by a change in coil diameter or variation of the spacing between turns. It should be possible to obtain such a sinusoidal distribution, however.

SUMMARY OF RESULTS

In this investigation of ion-cyclotron-wave generation using an electrostatically shielded Stix-type rf coil the following results were obtained:

1. No major difficulties were encountered in using an external electrostatic shield between the exciting coil and the plasma. A nonsinusoidal magnetic field was obtained, however, because of capacitance between the coil and neighboring conducting elements.

2. Power absorption data are qualitatively in agreement with other investigators in the field in that two peaks were observed at magnetic fields just above the atomic-ion-cyclotron field.

3. A tentative explanation for the two peaks observed in the power-absorption and magnetic-probe measurements is that two different wavelengths, 44.5 and 89 cm, are being generated as a result of the non-sinusoidal magnetic field of the rf coil. This explanation differs from previous interpretation that the two peaks result from generation of a single wave plus a particle resonance.

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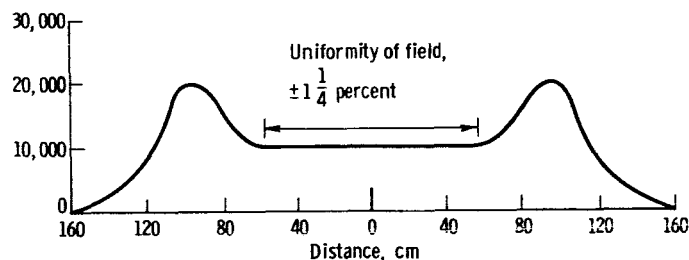
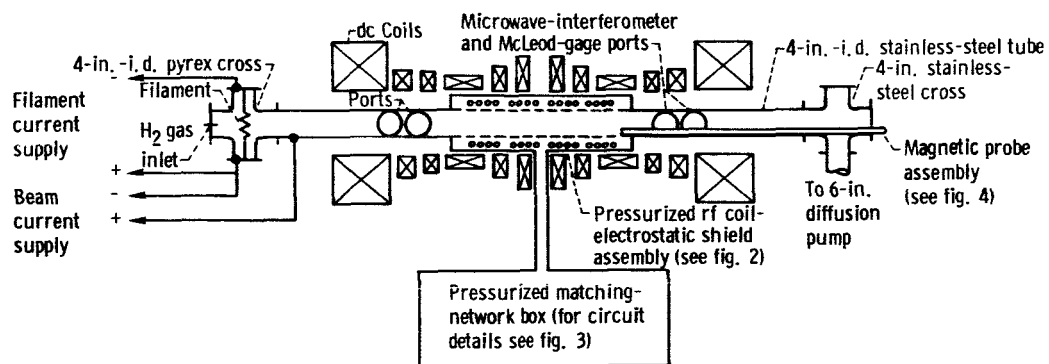


Figure 1. - Configuration of ion-cyclotron resonance apparatus 2B (ICRA 2B).

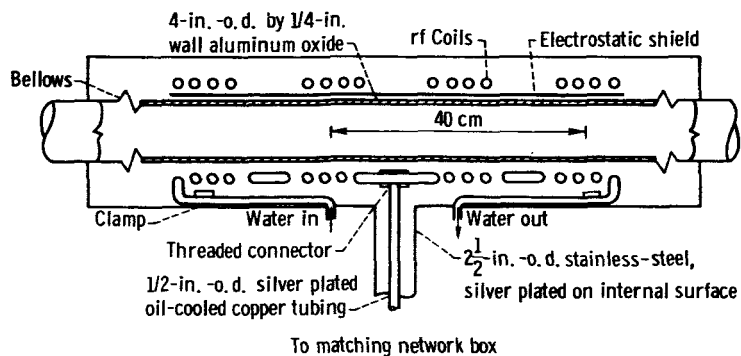
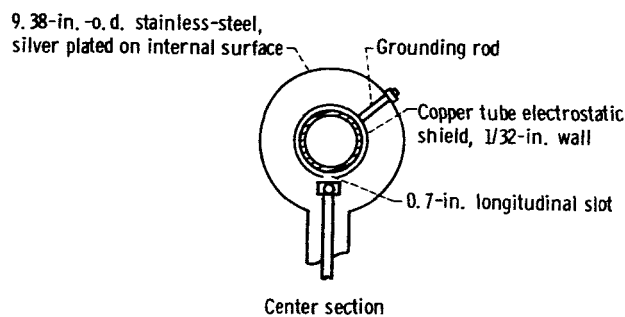


Figure 2. - Details of rf-coil electrostatic-shield assembly.

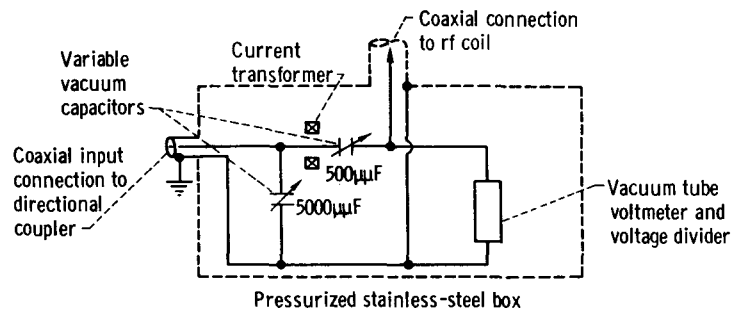


Figure 3. - Electric circuit for 50-ohm matching network.

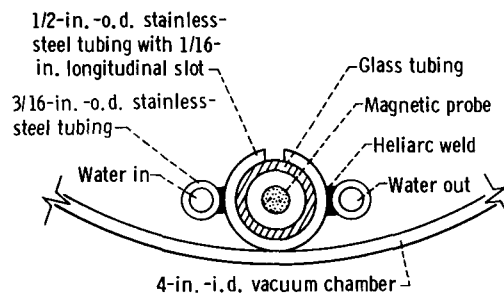


Figure 4. - Water-cooled magnetic-probe holder.

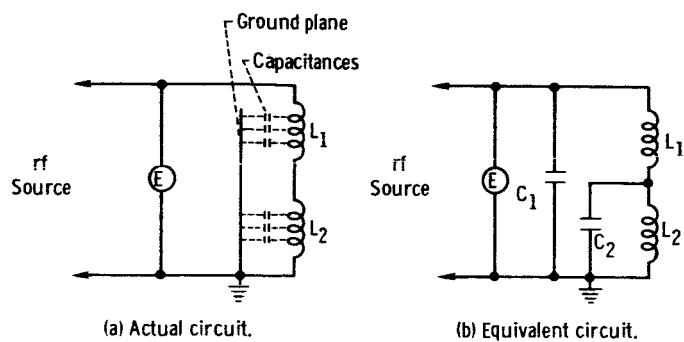


Figure 5. - Model used to show nonuniform current distribution.

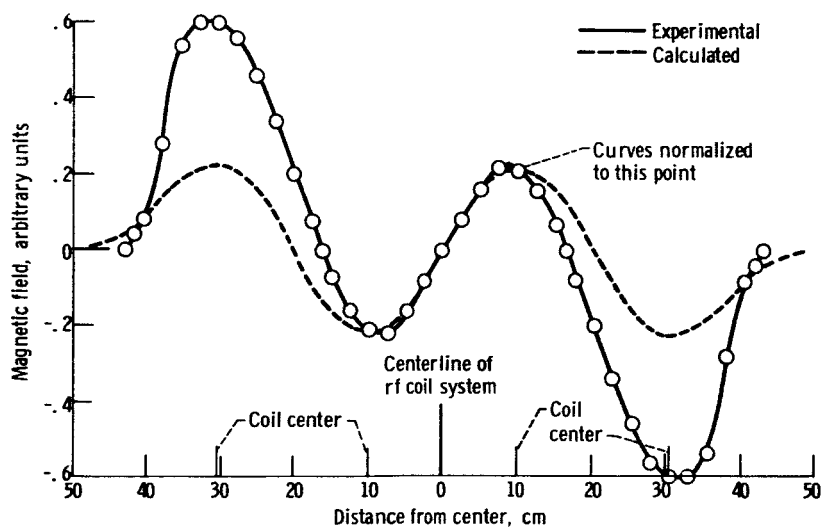


Figure 6. - Calculated and experimental values of axial magnetic field of rf coil.

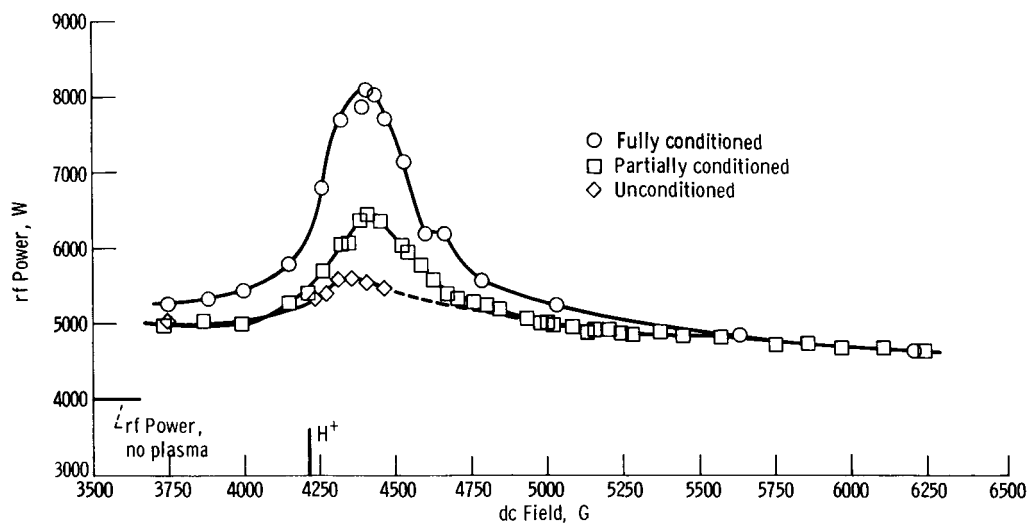


Figure 7. - Effect of apparatus conditioning on rf power. Pressure, 2 μ ; discharge current, 15 A; coil current, ~130 A.

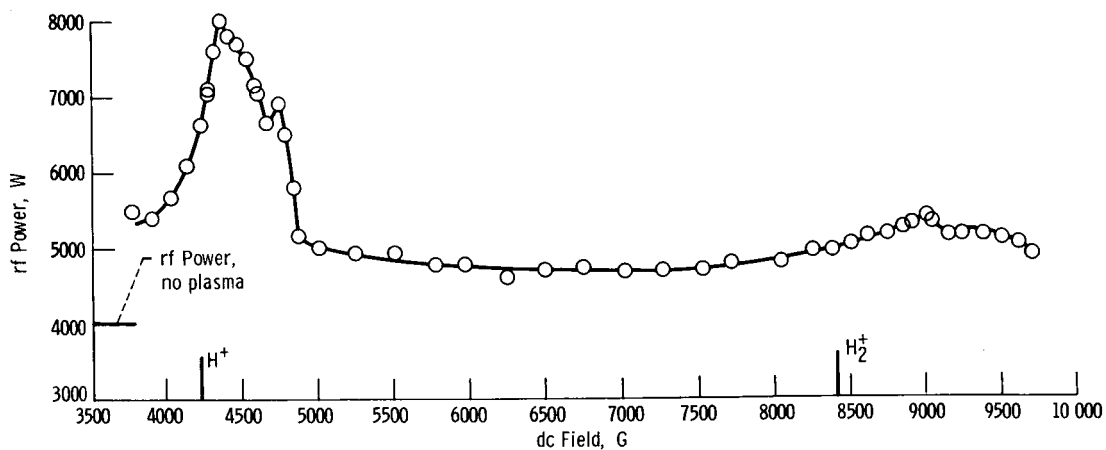


Figure 8. - Effect of magnetic field on rf power. Pressure, 2 μ ; discharge current, 20 A; coil current, ~130 A.

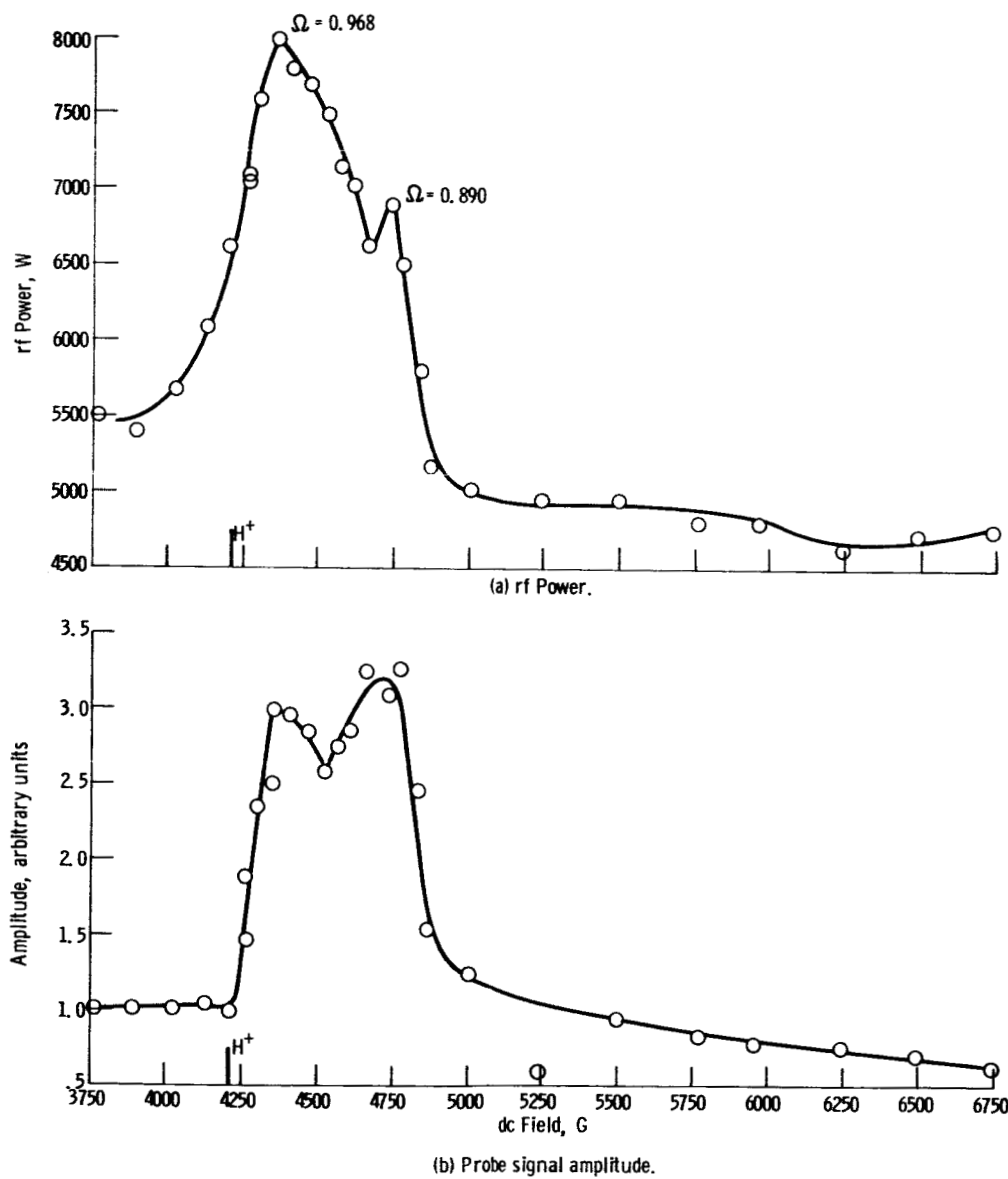


Figure 9. - Effect of magnetic field on rf power and probe signal amplitude. Pressure, 2μ ; discharge current, 20 A; coil current, ~ 130 A.